

# Observations of Free-Free and Anomalous Microwave Emission from LDN 1622 with the 100 m Green Bank Telescope

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Accepted xxxx xx xx. Received xxxx xx xx

## ABSTRACT

LDN 1622 has previously been identified as a possible strong source of dust-correlated Anomalous Microwave Emission (AME). Previous observations were limited by resolution meaning that the radio emission could not be compared with current generation high-resolution infrared data from *Herschel*, *Spitzer* or *WISE*. This *Paper* presents arcminute resolution mapping observations of LDN 1622 at 4.85 GHz and 13.7 GHz using the 100 m Robert C. Byrd Green Bank Telescope. The 4.85 GHz map reveals a corona of free-free emission enclosing LDN 1622 that traces the photo-dissociation region of the cloud. The brightest peaks of the 4.85 GHz map are found to be within  $\approx 10\%$  agreement with the expected free-free predicted by SHASSA H $\alpha$  data of LDN 1622. At 13.7 GHz the AME flux density was found to be  $7.0 \pm 1.4$  mJy and evidence is presented for a rising spectrum between 13.7 GHz and 31 GHz. The spinning dust model of AME is found to naturally account for the flux seen at 13.7 GHz. Correlations between the diffuse 13.7 GHz emission and the diffuse mid-infrared emission are used to further demonstrate that the emission originating from LDN 1622 at 13.7 GHz is described by the spinning dust model.

**Key words:** radio continuum: ISM – diffuse radiation – radiation mechanisms: general – ISM: photodissociation region (PDR) – dust, extinction – individual objects: LDN 1622

## 1 INTRODUCTION

Dust-correlated anomalous microwave emission (AME) has been observed in the frequency range 10 – 60 GHz and has a spectrum distinct from other sources of Galactic emission in the same range, such as free-free, synchrotron and the cosmic microwave background (CMB) (Kogut et al. 1996; Leitch et al. 1997; de Oliveira-Costa et al. 2004; Gold et al. 2011). Evidence of AME has been found in molecular clouds (Watson et al. 2005; Casassus et al. 2008; Planck Collaboration Early XX 2011), HII regions (Dickinson et al. 2009; Tibbs et al. 2012), Lynds dark clouds (Casassus et al. 2006; AMI Consortium et al. 2009), large scale diffuse Galactic dust (Peel et al. 2012) and in one external galaxy (Murphy et al. 2010). As AME is present in many different environments, it may become an important new tool for studying the interstellar medium (ISM).

There have been several proposed mechanisms for AME. The spinning dust model is currently the favoured explanation for AME (Draine & Lazarian 1998a,b). The other possible explanations for AME include: free-free emission

from shock-heated gas (Leitch et al. 1997); flat spectrum synchrotron emission (Bennett et al. 2003) and magnetic dipole emission from dust grains (Draine & Lazarian 1999). For the purposes of this *Paper* the spinning dust model is assumed to be the origin of AME. The spinning dust model proposes that the rapid rotation of small dust grains with electric dipoles generates AME (Draine & Lazarian 1998a,b; Ali-Haïmoud, Hirata & Dickinson 2009; Hoang, Draine & Lazarian 2010; Ysard, Miville-Deschênes & Verstraete 2010). Dust grains in the interstellar medium can be broadly separated into big grains (BGs;  $> 0.1\mu\text{m}$ ), very small grains (VSGs;  $< 0.1\mu\text{m}$ ) and disc-like molecules known as Poly-Aromatic Hydrocarbons (PAHs; as small as tens of atoms) (Desert, Boulanger & Puget 1990; Li & Draine 2001). VSGs generate mid-infrared (MIR) continuum emission, whereas PAHs are observed as several MIR emission lines between 1 –  $12\mu\text{m}$  (Tielens 2008). The spinning dust model assumes that only the VSGs and PAHs contribute to AME. Therefore strong morphological correlations are expected between AME and mid-infrared emission.

Recent *Planck* observations have identified numerous possible AME sources within the Galaxy that can be described by the spinning dust model. The Perseus and  $\rho$ -Ophiuchus molecular clouds were identified as the two sources that provide strong evidence in support of the spinning dust model (Planck Collaboration Early XX 2011; Planck Collaboration Int. XV 2014). However, it is still unknown whether PAHs or VSGs contribute the most towards the generation of AME and whether it is pervasive throughout the ISM. By observing AME at resolutions comparable to current infrared space observatories, such as *WISE*, *Spitzer* and *Herschel*, it should be possible to determine the dust grain population generating AME.

A full-width half-maximum (FWHM) resolution of 1 arcmin or smaller would be required to compare radio observations with infrared (IR). These resolutions are easily obtainable using interferometric radio observations. However, AME has a largely extended and diffuse morphology and interferometers are only sensitive to particular angular scales. Typically if the angular size of a source extends beyond the synthesised beam resolution of the interferometer, the flux from the larger angular scales is lost (Thompson, Moran & Swenson 2007). The sensitivity of interferometers to extended emission can be improved by using models of the u-v coverage but it not possible to recover information from unobserved scales. Single-dish radio observations are able to measure all the flux from a source. This makes single-dish observations ideal for measuring diffuse and extended sources. A difficulty with single-dish observations is that they require extremely large apertures in order to achieve resolutions comparable to the IR observatories. The 100 m Robert C. Byrd Green Bank Telescope (GBT) is one of the few radio telescopes with a dish large enough to reach FWHM resolutions smaller than  $\approx 1$  arcmin.

Lynds Dark Cloud LDN 1622 is a starless cometary cloud in the vicinity of the Orion B molecular cloud, *North-East* of Barnard's Loop (Maddalena et al. 1986). The *West* and *South* sides of LDN 1622 are traced by a bright H $\alpha$  corona that is clearly visible in the SHASSA images (Gautad et al. 2001) and is illuminated by the nearby Ori OB1b stellar association (Kun et al. 2008). The bright H $\alpha$  corona may also trace the Photon-Dominated Region (PDR) around LDN 1622. The Cosmic Background Interferometer (CBI) observed LDN 1622 at 31 GHz with an 8 arcmin synthesised beam and found a strong correlation between the emissions from the PDR seen by CBI 31 GHz and IRAS 12  $\mu$ m (Casassus et al. 2006). The IR correlations seen by CBI were attributed to heated VSGs within the PDR generating AME. Earlier observations of LDN 1622 over 5 – 10 GHz with the 140 ft Green Bank Telescope also identified LDN 1622 as possibly one of the first compact sources of AME (Finkbeiner et al. 2002). Evidence for AME was also found by the CBI at 31 GHz in the nearby cloud LDN 1621 (L1621), which is approximately 30 arcmin *North* of LDN 1622 (Dickinson et al. 2010). The proximity of LDN 1621 to LDN 1622 suggests they may share similar grain populations and therefore if AME is found in one cloud it may be present in the other.

This *Paper* presents new observations of LDN 1622 at 4.85 GHz (C-band) and 13.7 GHz (Ku-band) taken with the GBT. These are the first extended mapping of a Lynds dark cloud with high resolution radio observations from a single-

dish radio telescope. This *Paper* is structured as follows: Section 2 discusses the observations, data processing and ancillary data. Section 3 describes GBT maps of LDN 1622. Section 4 compares the emissions seen at 4.85 GHz and 13.7 GHz by the GBT to archival and ancillary observations of LDN 1622. Finally, Section 5 summarises the findings in this *Paper*.

## 2 OBSERVATIONS AND DATA PROCESSING

### 2.1 GBT Observations

The GBT is a 100 m diameter fully-steerable single-dish radio telescope that operates at frequencies less than 100 GHz. The observations were taken over several days in January 2007 and one extra observation was made the following year in January 2008. The observed time on source for C-band was 5 hours and for Ku-band 7.5 hours.

Observations were made at two frequencies: 4.85 GHz (C-band) and 13.7 GHz (Ku-band). Both C-band and Ku-band observations used the Digital Continuum Receiver (DCR) on the GBT. The observations used all the 16 frequency channels available to the DCR for each frequency, this provided a bandwidth of 1.28 GHz for C-band and 3.5 GHz for Ku-band. The sample integration time was 0.2 seconds. The C-band receiver has a single beam with a Full-Width Half-Max (FWHM) resolution of 2.6 arcmin at 4.85 GHz. At Ku-band the GBT has two receivers with independent beams, both with a FWHM resolution at 13.7 GHz of 55 arcsec. One receiver is located in the central focal position of the GBT and will be referred to in this *Paper* as the central beam. The other Ku-band receiver is displaced by 330 arcsec in the cross-elevation direction and will be referred to as the off-centre beam. Both C-band and Ku-band operated in dual polarisation mode, measuring left (LL) and right (RR) circularly polarised radiation simultaneously. It was assumed that the emission from LDN 1622 would have negligible circular polarisation, therefore total intensity could be obtained by averaging together the LL and RR data.

On-The-Fly (OTF) mapping was used to scan across the regions in Right Ascension (R.A.) and Declination (Decl.), at a speed on the sky of 1 arcmin s<sup>-1</sup>. This resulted in a series of nested scans across both regions. The C-band observations mapped a region of 35 arcmin  $\times$  35 arcmin centred upon LDN 1622 at R.A. = 5<sup>h</sup>54<sup>m</sup>29<sup>s</sup>, Decl. = 1<sup>°</sup>45'36". The Ku-band observations mapped a 12 arcmin  $\times$  12 arcmin sub-region of LDN 1622 centred upon R.A. = 5<sup>h</sup>54<sup>m</sup>16<sup>s</sup> and Decl. = 1<sup>°</sup>49'52". In order to obtain the desired total integration time per beam in the final map, multiple scans of the same region were made. By observing in this way using OTF mapping, instead of integrating each beam using a pointed observation, the effect of long timescale correlated 1/*f* noise caused by the atmosphere or receivers could be minimised.

The theoretical thermal noise of the receiver was calculated using:

$$\left(\frac{\sigma}{\text{mK}}\right) = \frac{44.2}{\mu} \frac{\left(\frac{T_{sys}}{\text{K}}\right)}{\sqrt{\left(\frac{\Delta\nu}{\text{GHz}}\right)\left(\frac{\tau}{\text{sec}}\right)}}, \quad (1)$$

where  $T_{sys}$  is the measured system temperature,  $\Delta\nu$  is the

bandwidth of the receiver,  $\tau$  is the sample integration time and  $\mu$  is the aperture efficiency. The aperture efficiency for C-band was 75% and for Ku-band 72%. The theoretical noise levels were 2.34 mK and 2.1 mK for C-band and Ku-band respectively. The measured median noise level for all the C-band and Ku-band scans were 16.9 mK and 13.0 mK. Comparing the median noise level to the theoretical noise level for C-band and Ku-band revealed that the measured noise was 7.2 and 6.2 times higher respectively. The higher than expected noise for both frequencies was due to  $1/f$  noise contamination in the data. Reducing the effect of  $1/f$  noise on the data is discussed in the following Section.

## 2.2 Calibration and Processing

The internal noise diode of the receiver, with a known equivalent antenna temperature for each receiver ( $T_{cal}$ ), was used to calibrate the time-ordered-data (TOD) into units of brightness temperature using the following equation:

$$T_b = \frac{T_{cal}}{2} \frac{V_{on} + V_{off}}{\langle V_{on} - V_{off} \rangle} - \frac{T_{cal}}{2}. \quad (2)$$

The noise calibration diode was injected into every other sample in the TOD at a frequency of 5 Hz.  $V_{on}$  describes the receiver voltage when the noise diode was on and  $V_{off}$  describes the receiver voltage when the noise diode was off.

To check the diode calibration, the flux densities of 3C161, 3C48 and 3C147 were measured at the beginning and half-way through each observing session. The measured flux densities based on the diode calibration were then compared to the predicted flux densities from the source models described in Ott et al. (1994). The flux densities of 3C161, 3C48 and 3C147 measured at C-band and Ku-band after calibrating with the diode were all found to be within 5% of the predicted flux densities.

The opacity of the atmosphere at radio wavelengths is dependent on the water vapour content of the air and the elevation of the observation. Over the several days of observing the relative humidity varied considerably, between 0% and 90%, and the elevation of the observations varied by 10 degrees. Measurements of zenith opacity from weather stations near to the GBT were used to estimate the effect of atmospheric opacity on the data. The maximum attenuation was estimated to be <0.05% and <2.6% for C-band and Ku-band. As these corrections are less than the flux density calibration accuracy, no atmospheric absorption corrections were applied to either C-band or Ku-band.

The emission from ground-based radar and geostationary TV satellites peak at around the C-band and Ku-band frequencies. These terrestrial sources of radio emission are considered radio frequency interference (RFI) and completely dominate astronomical sources. Several scans were found to be RFI contaminated. These scans were identified by comparing the peak signal in each scan to the thermal noise limit of the receiver. Scans containing any source with a brightness greater than 20 times the receiver noise were flagged as RFI contaminated and removed.

Time correlated noise within the TOD caused by the gain fluctuations in the receiver amplifiers or the instability of atmospheric water vapour can increase the effective noise of the TOD to be many times higher than the receiver thermal noise limit. This type of noise is known as  $1/f$  noise due

to the effect it has on the shape of the TOD power spectrum. The spectrum of  $1/f$  can be approximated by a power-law (Seiffert et al. 2002):

$$P_\nu = \sigma_w^2 \left[ 1 + \left( \frac{\nu_{knee}}{\nu} \right)^\alpha \right], \quad (3)$$

where  $\sigma_w$  describes the thermal noise,  $\nu_{knee}$  is the knee frequency and  $\alpha$  is the spectral index of the  $1/f$  noise. At the knee frequency the TOD thermal noise and low-frequency  $1/f$  noise contribute equally to the spectral density of the TOD. The spectral index describes the power of the  $1/f$  noise, with typical values range between 1 and 2.

When OTF mapping continuum sources,  $1/f$  noise can cause stripes in the scan directions of the final map and obscure the astronomical signal. This is a limitation of single-dish radio observations however there are methods for mitigating  $1/f$  noise both during the observations and when data processing.

During the observations, the effect of  $1/f$  noise on the astronomical signal was reduced by slewing the telescope as fast as possible. The data in each scan can be assumed to have  $1/f$  noise contributions from the receiver and the atmosphere. The noise of each scan was assumed to have a fixed knee frequency. By slewing the telescope faster, the time for a scan can be made shorter than the timescale of the  $1/f$  noise variations. The limit on how much  $1/f$  noise can be removed in this way is a balance between the knee frequency of the noise and the physical constraints of the telescope. In the case of these observations the GBT could not slew fast enough to remove all the  $1/f$  noise contamination.

During the data processing stage scans containing high levels of  $1/f$  noise contamination were removed. The ratio between the variance of pairs of data separated by two different lags was used as the metric to determine the  $1/f$  contamination of a scan. The variance of the difference between the TOD and the TOD lagged by  $\tau$  samples ( $d_{\tau+i} - d_i$ ) was defined as,

$$\sigma_\tau^2 = \sigma^2(\{d_\tau - d_0, d_{\tau+1} - d_1, \dots, d_{\tau+i} - d_i\}). \quad (4)$$

Differencing the TOD separated by a lag of 1 sample,  $\tau = 0.2$  seconds, results in a set of data with a variance equal to the white-noise limit of the TOD but increased by a factor of  $\sqrt{2}$ . The white-noise limit of the TOD can then be compared with the variance of the TOD differenced with different lags. As the lag time increases, more  $1/f$  noise will contaminate the differenced TOD. Therefore the ratio between the differenced TOD variance and white-noise limit increases. The variance of the differenced TOD lagged by a  $\tau = 1$  second (5 samples) was chosen to compare with the white-noise limit of the TOD. The lag time was chosen to be slightly shorter than the timescale of the median knee frequency of the data,  $\gtrsim 0.7$  Hz. This ensured that only scans with a large  $1/f$  noise contribution were filtered.

The ratio between the lagged differenced TOD and the white-noise limit was measured for each scan as

$$R = \frac{\sigma_\tau}{\sigma_w}. \quad (5)$$

The metric  $R$  defines the ratio of the lagged differenced TOD variance ( $\sigma_\tau$ ) and the white noise limit ( $\sigma_w$ ). If a scan exceeded a cut-off value for  $R$  it was discarded. Many different cut-off values for  $R$  were used to generate difference maps using jack-knives of the data. The optimal cut-off for  $R$  was

determined when the noise in the difference maps was at a minimum. A value of 2.3 for  $R$  was found to minimise the noise in the difference maps at both frequencies. For C-band and Ku-band, 50 % and 14 % of the scans exceeded the  $R = 2.3$  maximum cut-off noise variance ratio and were removed.

A summary of the observations and map noise limits can be found in Table 1.

### 2.3 Map-Making

The maximum-likelihood (ML) map-making technique was used as the final step in reducing  $1/f$  in the final maps. ML map-making was originally developed for CMB experiments as a way of recovering the weak CMB signal from  $1/f$  noise dominated observations (Borrill 1999; Natoli et al. 2001; Doré et al. 2001). ML map-making is the ideal method to use for these observations as for many scans the emission from LDN 1622 was dominated by  $1/f$  noise.

The advantage of ML map-making is that it uses an estimated full covariance matrix of the noise to find an optimal solution for the signal in the TOD. The estimated covariance matrix accounts for both the instrumental and atmospheric contributions to the  $1/f$  noise. The work in this *Paper* used an independently developed ML map-maker. The ML map-makers ability to recover signal from a  $1/f$  contaminated set of TOD was tested using simulations. A summary of the ML map-making technique, this implementation and simulations are described in Appendix A.

### 2.4 Description of Ancillary Data

In this *Paper* the GBT data at C-band and Ku-band were compared with existing data at radio, IR and optical frequencies. Section 3.2 discusses the ancillary data and its relationship to the emissions at C-band and Ku-band in more detail.

Ancillary interferometric radio data at 15.7 GHz was provided by the Arcminute Microkelvin Imager (Yvette Perrot; private communication) (Zwart et al. 2008, AMI). The AMI Small Array (SA) consists of 10 3.7 m diameter dishes. The AMI SA has baseline spacings between 5 – 20 m and a synthesised beam of 3 arcmin.

FIR observations were obtained from publicly available archival ESA *Herschel* Space Observatory (Pilbratt et al. 2010) data. The archival data were SPIRE (Griffin et al. 2010) and PACS (Poglitsch et al. 2010) photometry of Orion B at 500  $\mu\text{m}$ , 350  $\mu\text{m}$ , 250  $\mu\text{m}$  and 160  $\mu\text{m}$ . The FWHM resolutions of each band were approximately: 35.2 arcsec, 23.9 arcsec, 17.6 arcsec and 11.7 arcsec. The SPIRE and PACS observations were made in parallel mode with observation identification numbers OBSID: 1342205074 and OBSID: 1342205075. The *Herschel* maps were reduced using the SPG v11.1.0 pipeline. For the PACS data, the level 2.5 MADMAP products were used. The SPIRE level 2 products with an absolute background correction applied from *Planck* data were used. PACS 70  $\mu\text{m}$  data were also available but were not used because of poor signal-to-noise.

MIR data were provided by the Wide-field Infrared Sky Explorer (Wright et al. 2010, *WISE*). In this *Paper* only the 22  $\mu\text{m}$  and 12  $\mu\text{m}$  observations were used in order to reduce

**Table 1.** Receiver and observational properties of the 4.85 GHz (C-band) and 13.7 GHz (Ku-band) datasets.

Central Frequency (GHz)	4.85	13.7
Bandwidth (GHz)	1.28	3.5
No. Beams	1	2
Back end	DCR	DCR
Observing mode	On-The-Fly	On-The-Fly
Hours Observed (Hours)	5	7.5
Beam (FWHM)	2.6 arcmin	55 arcsec
Smoothed Beam (FWHM)	3 arcmin	1.2 arcmin
Sky scan speed ( $\text{arcmin s}^{-1}$ )	1	0.5
Data Flagged (percent)	50	14
Map Noise ( $\text{mJy beam}^{-1}$ )	4.3	5.5
Confusion limit <sup>1</sup> ( $\text{mJy beam}^{-1}$ )	$\approx 0.45$	$\approx 0.03$
Map Noise (mK)	2.5	2.5
Confusion limit <sup>1</sup> (mK)	$\approx 0.9$	$\approx 0.05$
Field Width (arcmin)	35	12

the number of point sources contaminating the field. The FWHM resolution of the *WISE* 22  $\mu\text{m}$  map is 12 arcsec and the *WISE* 12  $\mu\text{m}$  map is 7.4 arcsec.

An archival Spitzer IRAC (Fazio et al. 2004) map of LDN 1622 at 8  $\mu\text{m}$  was used to supplement the WISE MIR data. Point sources from the Spitzer map were subtracted. The IRAC 8  $\mu\text{m}$  map has a FWHM resolution of  $\approx 1.98$  arcsec.

Optical H $\alpha$  data of LDN 1622 were taken from the Southern H-Alpha Sky Survey Atlas (Gaustad et al. 2001, SHASSA). The SHASSA H $\alpha$  data serves as a tracer for the free-free emission seen at C-band (Dickinson, Davies & Davis 2003). The SHASSA map has a FWHM resolution of 0.8 arcmin and can detect sources down to the level of  $\approx 2$  Rayleigh. The SHASSA continuum-subtracted maps contain numerous stellar artefacts around poorly subtracted bright sources. However, no significant stellar artefact contamination of the H $\alpha$  emission observed around LDN 1622 was visible.

## 3 RESULTS

### 3.1 GBT Maps

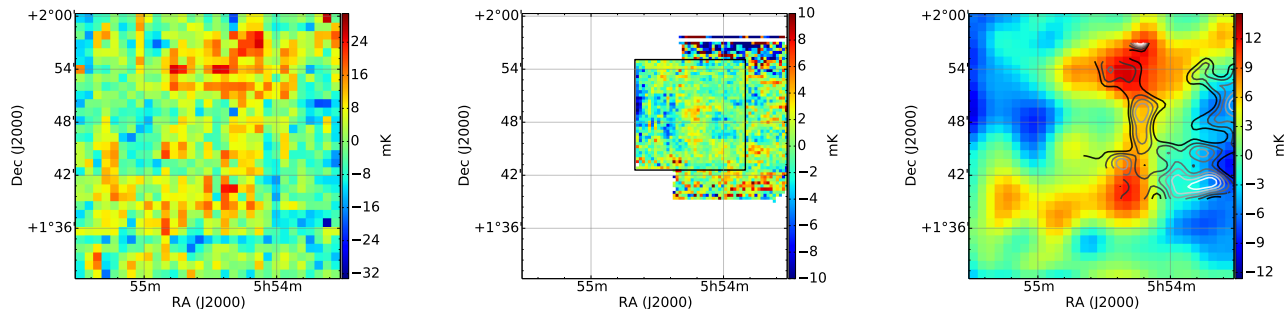
Fig. 1 presents the final C-band and Ku-band ML maps, both unsmoothed and smoothed. The unsmoothed C-band map has a FWHM resolution of 2.6 arcmin. The map pixel size for the C-band map is 57.6 arcsec ensuring 2.7 pixels across a beam. The pixel size was chosen to maintain Nyquist sampling across the field. The noise in the C-band map was estimated from jack-knifing RR and LL polarisation maps. The jack-knife map should contain only the white-noise and residual receiver  $1/f$  noise. In order to avoid

<sup>1</sup> Confusion limit calculated using

$$\frac{\sigma_c}{\text{mJy beam}^{-1}} = 0.2 \left( \frac{\nu}{\text{GHz}} \right)^{-0.7} \left( \frac{\theta}{\text{arcmin}} \right)^2, \quad (6)$$

which is a parametrised form of the calculation found in Condon (1974).





**Figure 1.** Final C-band and Ku-band maps as generated by the ML map-making method. The images are centred at R.A. =  $5^{\text{h}}54^{\text{m}}29^{\text{s}}$ , Decl. =  $1^{\circ}45'36''$  with dimensions  $30 \text{ arcmin} \times 30 \text{ arcmin}$ . *Left:* C-band map at the original 2.6 arcmin FWHM resolution. *Centre:* Ku-band map at the original 55 arcsec FWHM resolution. The black box marks the extent of the area observed by the central beam. *Right:* Overlay of smoothed Ku-band map contours on the smoothed C-band map. The contour levels are 0.1, 0.45, 0.8, 1.15, 1.5 and  $1.85 \text{ mJy beam}^{-1}$  for a 1.2 arcmin beam.

the higher noise towards the edge of the C-band map, the noise was estimated from a 20 arcmin diameter aperture in the centre of a difference map generated from jack-knife maps of the data. The pixel noise within the aperture was measured to be 2.5 mK or  $4.3 \text{ mJy beam}^{-1}$ .

The Ku-band map is shown alongside the C-band map in Fig. 1. The original resolution of the Ku-band map was 55 arcsec FWHM and the map has 2.7 pixels per beam FWHM with a pixel size of 20.5 arcsec. As with the C-band map, the pixel size was chosen to ensure Nyquist sampling across the map. The Ku-band map combines data from a central beam and an off-centre beam. The off-centre beam, which is displaced by 330 arcsec in azimuth from focal centre, observed a larger region than the central beam as the observations were made at several different Hour Angles. For this reason the Western edge of the map has lower sampling and far higher noise than the Eastern side of the map, which was observed by both beams. The region observed by both beams is marked in Fig. 1 and 2 with a box. In order to avoid the regions of high noise within the Ku-band map the noise in the map was measured from a difference map, generated from jack-knives of the data, inside an aperture of 6 arcmin diameter centred on the Ku-band source marked in Fig. 2. The noise was found to be 2.5 mK or  $5.5 \text{ mJy beam}^{-1}$ .

Fig. 1 also shows smoothed contours of the Ku-band map overlaid onto a smoothed C-band map. The Ku-band map was smoothed to 1.2 arcmin FWHM resolution and the C-band map was smoothed to 3 arcmin FWHM resolution. The smoothing kernel for both GBT maps was chosen to increase signal-to-noise while retaining the structure of the emission within the field. The noise level of the smoothed C-band map is 1.7 mK or  $2.9 \text{ mJy beam}^{-1}$  and the noise level of the smoothed Ku-band map is 0.8 mK and  $1.8 \text{ mJy beam}^{-1}$ .

### 3.2 Comparison with Multi-Frequency Data

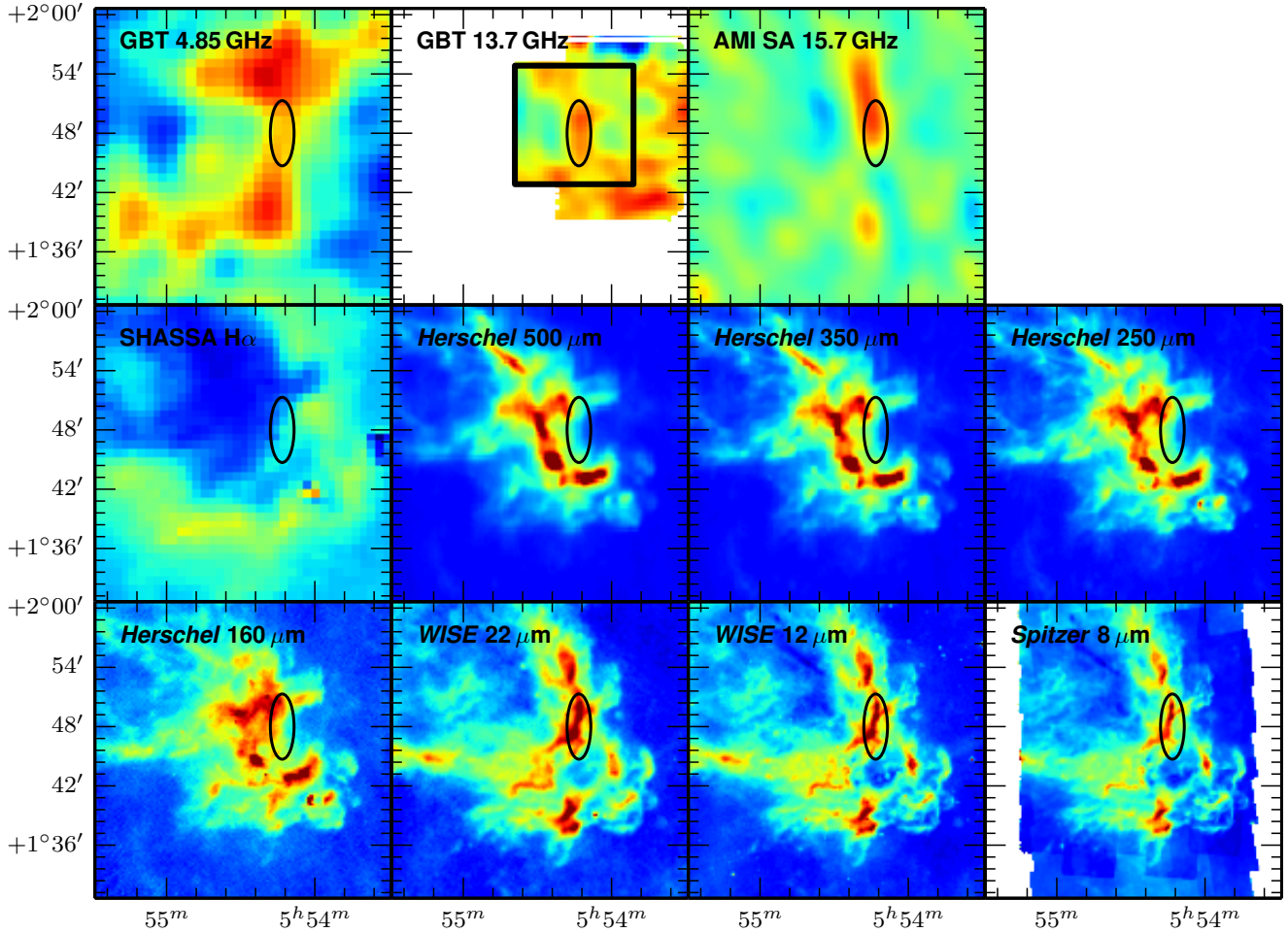
In Fig. 2 the smooth C-band and Ku-band maps are shown alongside ancillary maps of LDN 1622.

The C-band free-free emission in Fig. 2 can be seen to enclose LDN 1622 in a corona which spans from the *South-East* to the *North-West* and arches towards the *South-West* corner of the map. The  $\text{H}\alpha$  emission, a known tracer of free-

free emission (Dickinson, Davies & Davis 2003), can also be seen to have formed a corona of emission with a similar morphology to the corona of C-band emission. A key feature in the C-band and  $\text{H}\alpha$  maps is the Southern bar that spans the cloud *East* to *West*. This feature seems to correlate quite well between the C-band and  $\text{H}\alpha$  maps. The rest of the corona shows significant differences in morphology between the  $\text{H}\alpha$  and C-band emission, which can be mostly attributed to dust absorption of the  $\text{H}\alpha$  emission. Corrections for dust absorption are discussed in more detail in Section 4.1.

The corona, seen as both free-free and  $\text{H}\alpha$  emission, is likely associated with warm HII gas within the photo-dissociation region (PDR) around LDN 1622. The PDR around LDN 1622 is a transitional region, where on the Western side gas and dust are heated and ionised by far ultra-violet (FUV) radiation. Progressing Eastward the FUV flux is absorbed and the gas and dust eventually cool into the atomic and molecular phases (Hollenbach & Tielens 1999). The FIR and MIR structures shown in the *Herschel*, *WISE* and *Spitzer* maps around the aperture marked in Fig. 2 clearly show the separate stages occurring within the PDR. The MIR maps are tracing the emission from the warm VSGs, which are mixed with the ionised HII gas, as shown by the C-band data, and are exposed to the ionising interstellar radiation field. PDRs are environments rich in PAH molecules that have emission lines which lie within the passbands of the *WISE*  $12 \mu\text{m}$  and *Spitzer*  $8 \mu\text{m}$  maps (Tielens 2008). At longer wavelengths, such as in the FIR *Herschel* maps, the maps trace the location of cooler dust. The cooler dust is located in clumps near the core of LDN 1622 where the dust is shielded from the interstellar radiation field and is in thermal equilibrium with the environment.

In the smoothed Ku-band map, an elongated structure can be seen running *North-South* through the marked aperture in Fig. 2. The location of this aperture was also the location of the peak in emission seen at 31 GHz by CBI (Casassus et al. 2006). The weak emission from the elongated structure at Ku-band is also clearly visible in the Fig. 2 AMI 15.7 GHz SA map. Comparing the Ku-band map with the MIR maps reveals a shared morphology in the region of the aperture. The correlations between the MIR and Ku-band maps im-



**Figure 2.** Maps of LDN 1622 from GBT C-band and Ku-band observations and ancillary data. Each image is centred at R.A. =  $5^{\text{h}}54^{\text{m}}29^{\text{s}}$ , Decl. =  $1^{\circ}45'36''$  with dimensions of  $30 \text{ arcmin} \times 30 \text{ arcmin}$ . The elliptical aperture in each map marks the peak in Ku-band emission. A box surrounds the region observed by the central Ku-band beam in the Ku-band map. From the *top left* to the *bottom right* the images are: GBT C-band 4.85 GHz smoothed to a 3 arcmin beam and Ku-band 13.7 GHz smoothed to a 1.2 arcmin beam; AMI 15.7 GHz Small Array; SHASSA H $\alpha$ ; *Herschel* SPIRE 500  $\mu\text{m}$ , 350  $\mu\text{m}$  and 250  $\mu\text{m}$ ; *Herschel* PACS 160  $\mu\text{m}$ ; *WISE* 22  $\mu\text{m}$  and 12  $\mu\text{m}$ ; *Spitzer* IRAC 8  $\mu\text{m}$ .

plies a possible common source. The spinning dust model provides a possible explanation for the shared MIR and Ku-band morphology as it provides a mechanism for PAH molecules to emit at the Ku-band frequency (Ali-Haïmoud, Hirata & Dickinson 2009; Ysard, Miville-Deschênes & Verstraete 2010). A more detailed discussion of the Ku-band emission and its correlations with IR and radio emission can be found in Section 4.2.

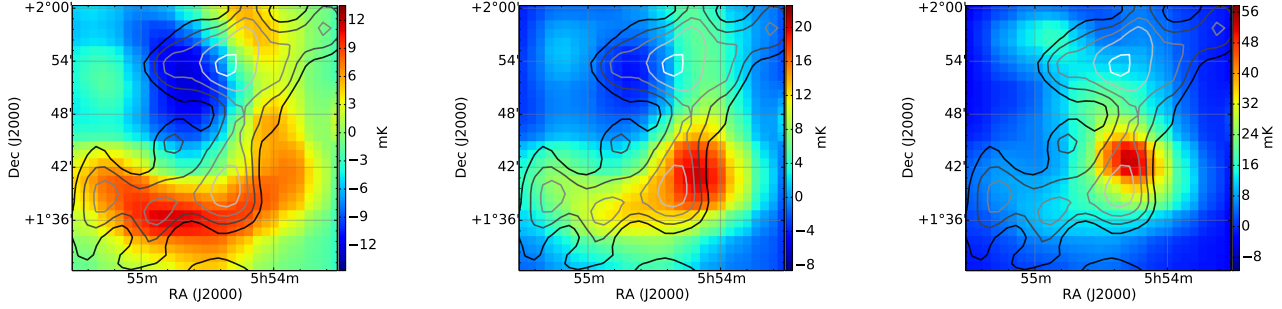
Note that a bright young stellar object (YSO) at R.A. =  $5^{\text{h}}54^{\text{m}}24.3^{\text{s}}$  and Decl. =  $1^{\circ}44'19''$  was removed from the FIR and MIR maps. The YSO has been briefly discussed in Bally et al. (2009) and is associated with the proto-stellar outflow HH 962.

## 4 ANALYSIS AND DISCUSSION

### 4.1 Free-Free Emission from LDN 1622

Ionised regions of HII gas generate both H $\alpha$  and free-free continuum emission. The brightness of H $\alpha$  emission is directly proportional to the density of the ionised hydrogen ( $n_{\text{H}}$ ) and the rate at which recombination occurs within the cloud, resulting in the H $\alpha$  transition. The brightness of free-free emission depends on the density of free electrons ( $n_{\text{e}}$ ) and ions within a region. In HII regions the free electrons are generated via ionisation therefore it is expected that  $n_{\text{e}} \approx n_{\text{H}}$ . Both emissions also depend on the electron temperature of the region, which is typically  $T_{\text{e}} \approx 10^4 \text{ K}$ . As both free-free and H $\alpha$  emissions share a common source, it is possible to directly relate the brightness of one emission to the brightness of the other (Dickinson, Davies & Davis 2003).

In Fig. 2 both the C-band and SHASSA maps show the same corona of HII tracing the *South* and *West* edges of



**Figure 3.** Overlay of smoothed C-band contours on  $H\alpha$  derived free-free maps assuming an electron temperature of 7000 K. The contour levels are 1, 3.75, 6.5, 9.25 and 12 in units of mK. The dust mixing fraction for each map from *left to right* is:  $f = 0.1, 0.5$  and  $1.0$ .

LDN 1622. The differences in the morphology of the radio free-free and SHASSA  $H\alpha$  emissions around LDN 1622 are primarily due to optical dust absorption of the  $H\alpha$  emission. Correcting for  $H\alpha$  dust absorption is complicated as the distribution of dust and HII gas is unknown. In this Section the radio free-free emission is estimated from the SHASSA map using the method outlined in Dickinson, Davies & Davis (2003) and compared with the observed C-band free-free emission. The extinction of the  $H\alpha$  by dust is estimated using a simple radiative transfer model and optical depths measured from the *Herschel* FIR maps.

FIR *Herschel* data of LDN 1622 were used to estimate  $H\alpha$  absorption,  $A(H\alpha)$ . The first step in deriving  $A(H\alpha)$  was to smooth all the *Herschel* maps to a common resolution. The 353 GHz optical depth ( $\tau_{353}$ ) was fitted for, pixel-by-pixel, over four *Herschel* bands. Each pixel was fitted with the modified black-body curve:

$$S_\nu = B_\nu(T_D)\tau_{353} \left( \frac{\nu}{353 \text{ GHz}} \right)^\beta, \quad (7)$$

where  $\beta$ , the emissivity index, the dust temperature,  $T_D$ , and  $\tau_{353}$  were all free parameters.  $B_\nu$  is a black-body curve dependent on the dust temperature.

IR optical depth was converted to hydrogen column density ( $N_H$ ) using:

$$\tau_{353} = \sigma_{e353} N_H, \quad (8)$$

where  $\sigma_{e353}$  is the mean whole sky dust opacity derived by Planck (Planck Collaboration Int. XI 2013). The hydrogen column density was then related to extinction ( $E(B-V)$ ) by assuming the relationship  $N_H/E(B-V) \approx 6.94 \times 10^{21} \text{ cm}^{-2}$  (Planck Collaboration Int. XI 2013). The  $H\alpha$  absorption factor was related to the measured extinction with,

$$A(H\alpha) = 0.81R(V)E(B-V) \quad (9)$$

The reddening value ( $R(V)$ ) for the ISM is typically  $\approx 3.1$  (Snedden et al. 1978; Schultz & Wiemer 1975). However,  $R(V)$  is observed to increase in denser regions of the ISM and even vary significantly between the edge of a dark cloud and its interior with a range of reddening values between  $3.5 < R(V) < 5.5$  (Vrba & Rydgren 1985, 1984). Considering the typical reddening values of other dark clouds and that LDN 1622 is quite a translucent cloud, a nominal reddening value of  $R(V) = 4$  was assumed.

The expected  $H\alpha$  emission ( $I_{em}$ ) was estimated from

the observed  $H\alpha$  emission ( $I_{obs}$ ) by applying the following  $H\alpha$  absorption model pixel-by-pixel to the SHASSA map:

$$I_{obs} = \frac{I_{em}}{\tau} \int_0^\tau e^{\tau' - \tau} d\tau' + (1 - f)I_{em} \quad (10)$$

The  $H\alpha$  optical depth ( $\tau$ ) was related to  $H\alpha$  absorption by  $\tau = A(H\alpha)/(2.5 \log_{10}(e))$ . The  $H\alpha$  absorption model assumed that a certain fraction ( $f$ ) of the HII gas and dust were mixed and in thermal equilibrium, while the remaining fraction of HII gas was in front of the dust and its  $H\alpha$  emission unabsorbed. The model does not consider HII gas completely behind the dust within LDN 1622 because the  $H\alpha$  emission in that case would be mostly absorbed resulting in large uncertainties in the estimated radio free-free. However, it is possible that some fraction of HII gas is completely obscured by dust behind LDN 1622.

After correcting for  $H\alpha$  absorption, the  $H\alpha$  brightness was converted to the equivalent radio free-free brightness using the method described in Dickinson, Davies & Davis (2003). The derived  $H\alpha$  to radio free-free conversion factor, assuming an electron temperature of  $T_e = 7000 \text{ K}$ , was  $0.28 \text{ mK R}^{-1}$  at 4.85 GHz. The final simulated free-free map was smoothed to a FWHM of 3 arcmin to match the smoothed C-band resolution. The median background of the simulated free-free map was subtracted to represent the effect of the map-making process removing the zero-level of the C-band data.

Three examples of simulated free-free maps with dust-gas mixing fractions of  $f = 0.1, 0.5$  and  $1.0$  are shown in Fig. 3 with C-band contours overlaid. At low mixing fractions the morphology and brightness of the Southern bar of the corona is reasonably well reconstructed by the simulated free-free map. At higher mixing fractions a bright core of emission forms in the *West* of the simulated LDN 1622 corona that is completely unrepresentative of the observed C-band emission. This implies that there is possibly very little dust-gas mixing occurring in the *South* of LDN 1622. The morphology and brightness of the *North-West* region of the corona appears significantly different in the predicted free-free maps to the observed C-band emission. The brightest region of the C-band emission in the *North-West* region of the corona is offset towards the *East* of the predicted free-free emission. An explanation for this is that much of the HII gas generating the free-free emission is behind the dust

in LDN 1622, therefore the  $H\alpha$  emission has been completely absorbed along that line-of-sight.

The discrepancies between the observed C-band emission and simulated free-free emission could be explained by the dust-gas mixing fraction ( $f$ ) varying across the cloud. It is possible that changes in the dust-gas mixing fraction is not the only explanation. The model assumed that both the 353 GHz dust opacity ( $\sigma_{e\,353}$ ) and optical reddening value ( $R(V)$ ) were both constant across LDN 1622. However, IR dust opacity and reddening are both linked to grain size distributions, which could be changing from the edge of LDN 1622 towards the core (Weingartner & Draine 2001).

The comparison between the SHASSA  $H\alpha$  and CBI 31 GHz observations of LDN 1622 (Casassus et al. 2006, Fig. 9) did not show any emission originating from the *North-Western* part of the corona that can be seen as a bright feature in the C-band map. Therefore an upper limit of 16.7 mK on the free-free emission was estimated from the contours of the CBI map. This upper limit is in agreement with the measured brightness temperatures of the C-band emission that range between 6 – 11 mK.

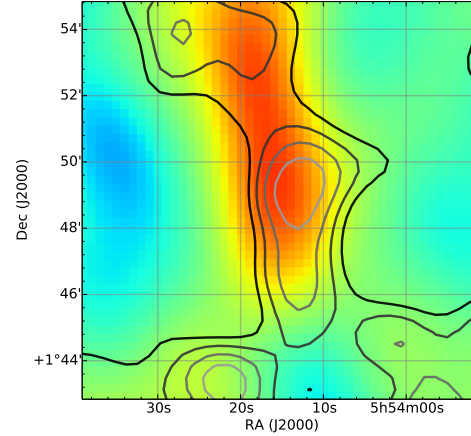
To summarise, the emission detected at C-band is seen to trace the HII corona of LDN 1622 and broadly agrees with the morphology of the SHASSA  $H\alpha$  map. The peak free-free brightness predicted by the  $H\alpha$  emission agrees within  $\approx 10\%$  of the peak observed C-band free-free emission for the bright  $H\alpha$  ridge in the *South* of LDN 1622 for dust mixing fractions of  $f \lesssim 0.1$ . Many of the differences in brightness and morphology between the predicted and observed free-free emission can be attributed to local variations in the dust-gas mixing fraction, reddening value or IR dust opacity over LDN 1622.

## 4.2 AME at Ku-band

In the smoothed 13.7 GHz Ku-band GBT map shown in Fig. 2, the aperture shown is centred on the peak in Ku-band emission at R.A. =  $5^{\text{h}}54^{\text{m}}13^{\text{s}}$ , Decl. =  $1^{\circ}47'49''$ . The aperture has a semi-major axis of 3 arcmin and a semi-minor axis of 1.25 arcmin.

Visually, Fig. 2 shows that there is some contribution of free-free emission from HII gas as well as MIR emission from dust grains within the aperture. This Section will determine whether the emission at Ku-band is AME or just free-free emission. This required calculating the expected free-free emission flux at Ku-band and assessing whether there is any significant morphological similarities between the emissions at Ku-band and the MIR.

Aperture photometry was used to measure the flux within the Ku-band aperture shown in Fig. 2. The aperture size of 3 arcmin by 1.25 arcmin was chosen by expanding the aperture axes from zero until the signal-to-noise ratio within the aperture was maximised. The uncertainty and background within the Ku-band aperture was estimated from an elliptical annulus around the aperture. The annulus had inner and outer semi-minor axes of 2.17 – 4.68 arcmin and inner and outer semi-major axes of 5.2 – 11.2 arcmin. The annulus inner and outer axes were chosen to enclose a sufficiently large sample of the C-band and Ku-band maps. Due to the Ku-band source being in close proximity to a number of diffuse sources, the estimated uncertainty on the flux density was measured from a difference map generated from



**Figure 4.** Overlay of smoothed GBT Ku-band contours on AMI SA colourscale. The contours are in units of  $\text{mJy beam}^{-1}$ , with a beam FWHM of 1.2 arcmin. The contour levels are 0.1, 0.45, 0.8 and  $1.15 \text{ mJy beam}^{-1}$ .

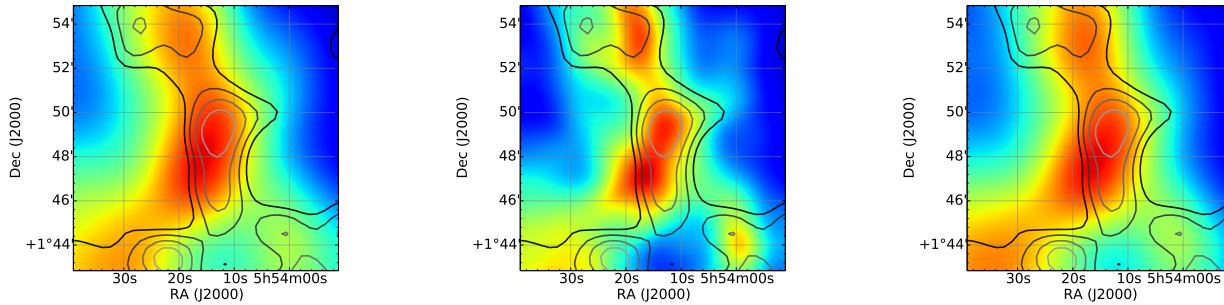
jack-knife maps of each observing day. By differencing different days, the difference map contained a statistically similar  $1/f$  noise contribution from the atmosphere and receivers as the Ku-band map. A five percent systematic uncertainty from the calibration of the data were added in quadrature to the measured uncertainties of the C-band and Ku-band flux densities.

The flux density within the Ku-band aperture shown in Fig. 2 was measured as  $7.0 \pm 1.4 \text{ mJy}$ . A free-free flux density of  $0.1 \pm 2.4 \text{ mJy}$  was measured from the C-band map within the same aperture. Inspection of the C-band map in Fig. 2 reveals that there must be free-free emission originating from within the aperture. Measuring the same aperture but using a background derived from the outside of the HII corona gives a C-band flux density of  $5.8 \pm 2.4 \text{ mJy}$  within the Ku-band aperture. However, over the region covered by the Ku-band map the free-free emission appears to be largely uniform and therefore zero with respect to the local background.

The measured fluxes from LDN 1622 were compared to the expected AME fluxes predicted by the spinning dust model and Interactive Data Language (IDL) code SP-DUST (Ali-Haïmoud, Hirata & Dickinson 2009; Silsbee, Ali-Haïmoud & Hirata 2011). The SP-DUST model expects nine environment parameters in order to estimate the expected AME flux from a region. The following is a brief description of each environment parameter and its value: the hydrogen number density ( $n_H = 10^4 \text{ H cm}^{-3}$ ), the gas temperature ( $T = 22 \text{ K}$ ), relative intensity of interstellar radiation field ( $\chi = 10^{-4}$ ), hydrogen ionisation fraction ( $x_H = 1 \text{ ppm}$ ), carbon ionisation fraction ( $x_C = 1 \text{ ppm}$ ), fractional abundance of molecular hydrogen ( $y = 0$ ),  $\text{H}_2$  formation rate ( $\gamma = 0$ ), rms of the dipole moment for dust grains ( $\beta = 9.3$ ) and the grain size distribution parameters corresponding to a given line in Weingartner & Draine (2001, Table 1, Line 7). A more detailed discussion of the SP-DUST environment parameters can be found in Ali-Haïmoud, Hirata & Dickinson (2009).

In this *Paper* the dark cloud environment parameters from Draine & Lazarian (1998b) are used. The expected





**Figure 5.** Overlay of smoothed Ku-band contours on the smoothed, point source removed MIR maps. *Left* *WISE* 22  $\mu\text{m}$ , *centre* *WISE* 12  $\mu\text{m}$ , *right* *Spitzer* IRAC 8  $\mu\text{m}$ . The contour levels are 0.1, 0.45, 0.8 and 1.15 mJy beam $^{-1}$  for a 1.2 arcmin beam.

hydrogen number density for a dark cloud was checked against a calculated estimate of the true hydrogen number density for LDN 1622. The distance to LDN 1622 is typically considered to be similar to the Orion molecular clouds ( $\approx 400$  pc) and it has an approximate angular size of 13 arcmin. Assuming the cloud is spherical and using the measured mean column density from *Herschel* FIR data ( $\approx 1.5 \times 10^{22}$  H cm $^{-2}$ ), the estimated hydrogen number density was found to be  $\approx 3000$  H cm $^{-3}$ , implying that the typical dark cloud  $n_H = 10^4$  H cm $^{-3}$  is a reasonable order of magnitude estimate for LDN 1622. The gas temperature parameter was matched to the mean dust temperature ( $T_D$ ) within the Ku-band aperture derived from the *Herschel* FIR data,  $T = T_D = 22 \pm 2$  K.

A key indication of spinning dust is a rising spectrum between  $\approx 10 - 30$  GHz. The expected flux density within the Ku-band aperture at 31 GHz was estimated using the CBI contours shown in [Casassus et al. \(2006\)](#) and scaling the flux density, assuming a smooth source, to the expected flux within just the Ku-band aperture. The spectral index between 13.7 GHz and 31 GHz was measured to be  $2.3 \pm 0.6$ . The uncertainty on the spectral index was estimated using:

$$\sigma_\alpha = \frac{1}{\log(\frac{\nu_2}{\nu_1})} \sqrt{\left(\frac{\sigma_1}{S_1}\right)^2 + \left(\frac{\sigma_2}{S_2}\right)^2}, \quad (11)$$

where  $\nu$  is a given frequency,  $S$  is the flux density at a given frequency and  $\sigma$  is the measured uncertainty. The spectral index derived from SPDUST between the same frequencies is 1.84, which is  $2.6 \sigma$  from the measured spectral index. The strong confirmation that the spectral flux density spectrum is rising between 13.7 GHz and 31 GHz and the agreement with the rising spectral index predicted by SPDUST is a good indication that spinning dust is present within LDN 1622 in the region of the Ku-band aperture.

A map of LDN 1622 using the AMI SA at 15.7 GHz was provided for the purposes of visual comparison with the Ku-band map. Fig. 4 shows the AMI SA data overlaid with Ku-band contours. As both observations are at similar frequencies, and both observations are sensitive to similar large scale structures there should be significant correlations between the AMI SA and Ku-band maps. Both the map and contours in Fig. 4 share the same large-scale elongated *North-South* structure. The most significant difference between the map and contours in Fig. 4 is the small displacement of the Ku-band GBT data towards the *West*.

It was shown in the previous discussion that the flux at Ku-band can be naturally accounted for by the spinning dust model and that there is a clear rising spectrum between 13.7 GHz and 31 GHz indicative of AME. However, if spinning dust is the origin of the Ku-band emission there should be significant correlations between Ku-band and MIR emission. The spinning dust model predicts that PAH molecules, VSGs or a combination of both are the source of AME. VSGs generate MIR continuum emission and PAH molecules emit bright MIR emission lines at 12.7  $\mu\text{m}$ , 11.3  $\mu\text{m}$ , 8.6  $\mu\text{m}$  and 7.7  $\mu\text{m}$  ([Tielens 2008](#)). The *WISE* 12  $\mu\text{m}$  and *Spitzer* 8  $\mu\text{m}$  passbands encompass these four PAH emission lines. The *WISE* 22  $\mu\text{m}$  passband only contains MIR continuum emission from the VSGs. Therefore, if PAH molecules contribute to the generation of AME, there should be a larger morphological correlation between the Ku-band and the 12  $\mu\text{m}$  and 8  $\mu\text{m}$  maps than with the 22  $\mu\text{m}$  map. It should be noted that it has been suggested that MIR emission in some HII regions and PDRs could be due to the formation of second-generation BGs in these environments ([Everett & Churchwell 2010](#); [Draine 2011](#); [Paladini et al. 2012](#)). There is a possibility that second-generation BGs are contributing to the MIR emission inside the PDR around LDN 1622, especially as the measured dust temperature within the PDR is quite warm,  $T_D = 22$  K. However, for this *Paper* BGs were assumed to not be contributing to the observed MIR emission.

In order to correlate the diffuse emission at Ku-band with the diffuse emission in the MIR, the MIR maps had to first be filtered of point sources. For both the *WISE* and *Spitzer* maps a number of point sources near to the elongated *North-South* structure were patched out. The patching process involved replacing the source with a 2nd-order polynomial and noise estimated from the background around the source. Due to the shorter wavelength and higher resolution of the *Spitzer* map there were a much larger number of weaker visible point sources, which were then removed using a median filter.

The patching and median filtering of the point sources left a number of artefacts in the diffuse structure of the MIR maps at scales comparable to the FWHM resolutions of the MIR maps. However, it is reasonable to assume that these artefacts had minimal effect on this analysis as all the MIR maps were smoothed considerably to match the 1.2 arcmin FWHM resolution of the smoothed Ku-band map.

The 1.2 arcmin FWHM, point source filtered *WISE* and *Spitzer* maps are shown in Fig. 5 with Ku-band contours overlaid. All three maps and the contours share the similar elongated *North-South* morphology. All the maps in Fig. 5 reveal that the peak in MIR emission also coincides with the location of the peak Ku-band emission. From visual comparison of the MIR maps with the Ku-band contours there is no clear indication that either the *Spitzer* 8  $\mu\text{m}$  or *WISE* 12  $\mu\text{m}$  maps, which contain the PAH emission lines, have stronger correlations with the Ku-band contours than the MIR continuum emission seen in the *WISE* 22  $\mu\text{m}$  map.

The Pearson's correlation coefficient,  $r$ , between the Ku-band map and each MIR map was measured to quantify any morphological correlations between the maps. The pixels in the maps were made quasi-independent by matching the pixel size to the FWHM of the maps. The Pearson correlations for each MIR map with the Ku-band map were found to be:  $r(22\ \mu\text{m}) = 0.54 \pm 0.13$ ,  $r(12\ \mu\text{m}) = 0.59 \pm 0.13$  and  $r(8\ \mu\text{m}) = 0.49 \pm 0.13$ . The uncertainties in  $r$  were estimated by bootstrapping the data and using the Fisher's  $r$  to  $z$  transform (Fisher 1915). The Pearson correlation measurements imply that there is a slightly higher correlation between the Ku-band and the MIR maps containing PAH emission lines. However, the uncertainties on the correlation coefficients reveal there is no significantly higher correlation between the Ku-band map and any one MIR map.

In summary this Section finds evidence to support the possibility that spinning dust in the form of either VSGs or PAHs is generating AME within the PDR of LDN 1622. The Ku-band emission measured by the GBT was found to have little free-free contamination. A rising spectrum, indicative of AME, was found between 13.7 GHz and 31 GHz. Finally, morphological correlations were found between the Ku-band emission and MIR emission.

## 5 CONCLUSION

This *Paper* has presented arcminute resolution mapping observations of the diffuse radio emission associated with LDN 1622 at C-band and Ku-band using the 100 m GBT. The goal of the observations was to measure free-free emission in the LDN 1622 region and identify and confirm the origin of the AME measured by previous observations.

A free-free corona associated with the PDR of LDN 1622 was revealed in the C-band maps. The emission seen in the SHASSA H $\alpha$  map was converted into the expected free-free brightness temperatures at C-band and the peak brightnesses were found to agree within  $\approx 10\%$  of the peak observed C-band emission. However, much of the the H $\alpha$  emission around LDN 1622 was shown to be affected by significant dust extinction. A simple model of the effect of dust extinction on the H $\alpha$  emission was shown to be not sufficient to correct for H $\alpha$  absorption over the whole cloud.

The Ku-band observations show a weak *North-South* elongated source inside the PDR of LDN 1622. The diffuse nature of the Ku-band emission made measurements of the flux density difficult. However, a weak source at the core of an elongated structure was identified. The flux density of the source was found to be consistent with previous observations of LDN 1622 and the flux density predicted by the spinning dust model of AME. Evidence was found for a

rising spectrum between the measured GBT 13.7 GHz emission and CBI 31 GHz emission, a strong indicator of spinning dust. Finally, the overall morphological structure of the Ku-band emission was found to weakly correlate with the emission from VSGs and PAH molecules at MIR wavelengths. It should be acknowledged that the emission at Ku-band is very weak and that the C-band observations do not entirely exclude the possibility that the emission at Ku-band is at least partially free-free emission. However, the correlations of the Ku-band emission with MIR and ancillary radio data, along with the measured rising spectrum of the source, do give reasonable confidence that the observed 13.7 GHz emission from LDN 1622 is spinning dust driven AME.

## ACKNOWLEDGEMENTS

SH acknowledges support from an STFC-funded studentship. CD acknowledges support from an STFC consolidated grant (ST/L000768/1), an STFC Advanced Fellowship, an EU Marie-Curie IRG grant under the FP7 and an ERC Starting (Consolidator) Grant (no. 307209). The authors would like to thank Roberta Paladini, Simon Casassus and Tim Pearson for helpful discussion and comments. The authors would also like to thank Yvette Perrott and the MRAO AMI group for providing the AMI SA observation of LDN 1622.

## APPENDIX A: MAXIMUM LIKELIHOOD MAP-MAKING

For this work an independent maximum-likelihood (ML) map-maker was developed. The map-maker follows the methods outlined in previous ML map-making papers (Borrill 1999; Natoli et al. 2001; Doré et al. 2001). The goal of ML map-making is to iteratively solve for the full noise covariance matrix of the input time-ordered-data (TOD) and remove stripes in the final map caused by  $1/f$  noise. The ML map-maker used in this *Paper* has been independently developed and implemented in Python<sup>2</sup> with Python-callable FORTRAN libraries, compiled using F2PY<sup>3</sup>. This Appendix briefly discusses simulations used to test the capabilities of the ML map-maker to remove  $1/f$  noise and recover a known input signal.

Fig. A1 shows an input map that was sampled to generate simulated noiseless TOD. Correlated noise was added to the TOD using the  $1/f$  noise model

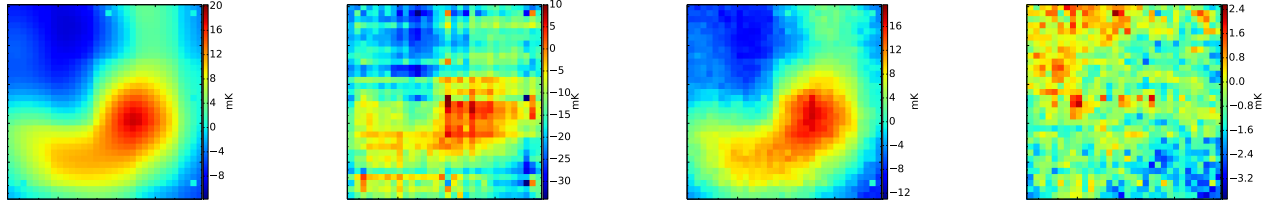
$$P_\nu = \left( \frac{\sigma}{\nu_s} \right)^2 \left[ 1 + \left( \frac{\nu_{knee}}{\nu} \right)^\alpha \right], \quad (\text{A1})$$

where  $\sigma$  is the receiver sensitivity,  $\nu_s$  is the sample rate,  $\nu_{knee}$  is the knee frequency,  $\alpha$  is spectral index and  $\nu$  is the frequency of a given spectral bin. The parameters for the simulated noise were chosen to match the noise of the C-band GBT data.

Fig. A1 shows how a simulated diffuse source contaminated with  $1/f$  can be reliably recovered using the ML

<sup>2</sup> Python Software Foundation. Python Language Reference, version 2.7. Available at <http://www.python.org>

<sup>3</sup> <http://sysbio.ioc.ee/projects/f2py2e/>



**Figure A1.** ML map-maker simulations. From *Left to Right* the maps show: noiseless input map; input map with  $1/f$  noise contamination; recovered map using ML map-making; difference between the noiseless input map and recovered map.

map-maker. The residual map shows only white-noise and a residual dipole. Typically, the ML map-maker cannot constrain the absolute background (monopole) and the dipole moment of the map as there is not sufficient information on those scales. However, the effect of the dipole can typically be ignored as only the smaller scale structures within a map are of interest.

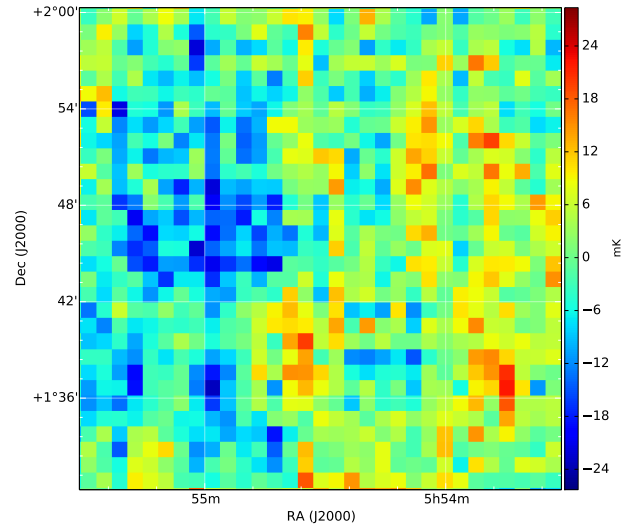
For real data, ML map-making cannot remove all the effects of  $1/f$  noise. This is because the noise in real data will typically be non-stationary meaning the  $\sigma$ ,  $\nu_{knee}$  and  $\alpha$  can all vary with time. The effect of non-stationary noise can be reduced by generating ML maps from subsets of the data where the noise is quasi-stationary. However, splitting the data up is not always possible because the integration time per pixel would be too low or constraints due to the scanning strategy used.

In the case of the GBT data, the observations were split by polarisation, as the receiver chains measured either LL or RR polarised emission. Therefore, each polarisation would have slightly different noise properties. A map for each polarisation was generated and both were averaged to produce the final map. In Fig. A2 a difference map generated from two jack-knife maps of the C-band data is presented. Each jack-knife map contained data from different days of observing. After ML map-making, the two jack-knife maps were used to generate a difference map that should contain statistically similar  $1/f$  noise as the C-band map.

Visually, Fig. A2 shows no clear evidence of the same structures seen in the C-band data, similar to the difference map of the simulated data in Fig. A1. This implies that there is no loss of signal when using ML map-making. However, Fig. A2 does show evidence of correlated noise and a gradient that have not been removed by the ML map-maker. This is due to the noise, even when the data are split into days with similar weather conditions, being only quasi-stationary. For this reason it is expected that the sensitivity of the C-band and Ku-band maps presented in this *Paper* will still contain residual  $1/f$  that cannot be reliably removed without degrading the signal from the astronomical source.

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**Figure A2.** Difference map of a jack-knife map generated from C-band data taken on the first day of observing and a jack-knife data generated from C-band data taken on the second and third days of observing.

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